AFCRL-228 DECEMBER 1960 LAS-TN-E173-10



40103

Research on Atmospheric Attenuation of Infrared Radiation

Howard T. Betz

Contract No. AF 19(604)-5877



THE UNIVERSITY OF CHICAGO



LABORATORIES FOR APPLIED SCIENCES



NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

_ _ _ _

Qualified requesters may obtain copies of this report from the Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia.

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C., for sale to the general public.

13 2/600 AFCRL-228 (4) \$ 1.60 (5) 501450

(1) LAS-TN-E173-10

10 13p. incl illus tables, 4 refs.

Research on Atmospheric Attenuation of Infrared Radiation

8 Howard T. Bets

(12) Contract No. AF 19(604)-5877

Prepared for
Geophysics Research Directorate
Air Force Cambridge Research Center
Air Research and Development Command
United States Air Force
Bedford, Massachusetts

LABORATORIES FOR APPLIED SCIENCES
6220 South Drexel Avenue
Chicago 37, Illinois

FOREWORD

This is the technical report on infrared transmission measurements through fog made at Arcata, California, during September and October 1959 under Contract No. AF 19(604)-5877. This report includes material presented in LAS-TN-E173-5; discussion included in paper presented in AMRAC meeting in Seattle, Washington, on 22 July 1960; and additional reduced transmission data (for which no particle data are available).

Principal personnel contributing to this program are: H. T. Betz, Lucien M. Biberman, C. M. Cohn, E. L. Hubbard, J. E. Jezewski, and R. J. Kauth.

LABORATORIES FOR APPLIED SCIENCES

Howard T. Betz Senior Physicist

Approved:

Lucien M. Biberman Associate Director

tranh E. A

Frank E. Bothwell

Director

ABSTRACT

This report summarizes the results of a measurement program conducted at Air Force Cambridge Research Center Fog Site at Arcata, California. The purpose of the Arcata fog experiment was (1) to collect data permitting a test of the applicability of Junge's law of the distribution of particle size as a consistent phenomenon of fogs and (2) to verify the predicted values of transmission based upon particle size a stribution. The experimental data presented tend to corroborate both Junge's law for particle size distribution and the theory for attenuation using this law.

A

TABLE OF CONTENTS

| ecti | on | | | | | | | | | | | | | | | | | | | | | | Page |
|------|------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|--|---|---|------|
| 1. | Introduction | • | • | • | • | | • | • | | • | | • | • | | • | • | | • | | | | • | 1 |
| 2. | Purpose of Experiment | | | | • | • | | • | • | • | • | | • | • | | | | | | | • | | 1 |
| 3. | Experimental Procedure | • | • | • | • | | • | | • | • | | | | | | • | | | • | | | • | 2 |
| 4. | Discussion of Results | | | | | | | | | • | | | | | • | | • | | | | | , | 4 |
| Li | st of References | | | | | | | | | | | | | | | | | | | | | | 13 |

1. INTRODUCTION

The principal purpose of this study is to determine the atmospheric attenuation of infrared radiation in a slant path of 5,000 to 40,000 feet in the wavelength range of 1 to 4 microns.

The program was amended to include (i) the determination of the infrared spectral transmission and attenuation through long paths of fog and (2) correlation of the observed attenuation with the density and size distribution of the fog particles and other pertinent physical parameters.

This report summarizes the results of a measurement program conducted at Air Force Cambridge Research Center, Fog Site at Arcata, California.

2. PURPOSE OF EXPERIMENT

The purpose of the Arcata fog experiment was twofold:

(i) To collect data permitting a test of the applicability of Junge's law of the distribution of particle size as a consistent phenomena of fogs which states that

$$n(r) = cr^{-p} , \qquad (1)$$

in which n(r) = concentration of particles per unit radius interval; <math>r = radius of particles (microns); and c, p = constants for Junge's law.

(2) To verify the predicted values of transmission based upon particle size distribution [1,2].*

Total scattering at λ due to above distribution is

$$\sigma = \int \pi r^2 K\left(\frac{r}{\lambda}\right) n(r) dr$$
,

in which $K(r/\lambda)$ is the scattering coefficient, or

$$\sigma = c\pi \int_{\mathbf{r}_0}^{\mathbf{r}_1} r^{(2-p)} K\left(\frac{\mathbf{r}}{\lambda}\right) d\mathbf{r}$$

in which \mathbf{r}_0 and \mathbf{r}_1 are the smallest and largest radii, respectively, for which Junge's law is valid in a particular fog..

*Numbers in brackets refer to entries in the List of References at the end of this report.

By change of variable to (r/λ) , and neglecting the lower limit,

$$\sigma = c \pi \lambda^{(3-p)} \int_0^{r_1/\lambda} \left(\frac{r}{\lambda}\right)^{(2-p)} K\left(\frac{r}{\lambda}\right) d\left(\frac{r}{\lambda}\right) . \tag{2}$$

The values for $K(r/\lambda)$ have been tabulated [3,4]. The integral in Eq. (2) can, in general, be integrated numerically and tables of σ as a function of λ , p, c, and r_4 can be devised. The parameters p, c, and r_4 can be measured experimentally.

3. EXPERIMENTAL PROCEDURE

To test the above relations, the experimental work was divided into two phases:

- (1) Direct measurement of particle size distribution.
- (2) Measurement of the fog transmission as a function of wavelength.

The particle size measurement was made with the Cambridge Research Center's cloud particle counter constructed by the Armour Research Foundation. This device counts particles and classifies them according to size by the light scattered from individual particles. Particles are classified into six sizes: 1 to 2, 2 to 4, 4 to 8, 8 to 16, 16 to 32, and larger than 32 microns in diameter.

Wherever possible the particle count data and transmission measurements were taken concurrently, and the particle counter was located adjacent to the optical path

Spectral measurements were made with essentially that equipment used by Kurnick et. al. [1]. The source, located in a small trailer, was a carbon arc with a 12-1/2 inch, f/5 collimator. The receiver was a Perkin-Elmer double-pass monochromator with a 12-1/2 inch, f/5 collector, and was located in a semi-trailer 200 yards from the source. The interval chopper of the monochromator was modified to give an 80-cps chopping rate. The detector was a 0.1- by 0.1-mm thermistor bolometer. Bandwidth of the amplifier was 20 cycles centered at 80 cps. The final record was made on an x-y recorder with the detector output on the x-axis and monochromator wavelength drum position on the y-axis. Using a sodium-chloride prism the instrument scanned from 1.5 to 12 microns in approximately 4 minutes. The slit width was varied to maintain a reasonable power level on the detector; i.e., the radiant power on the detector was maintained within a factor of 100 to 1. Figure 1 shows the actual variations in power level.

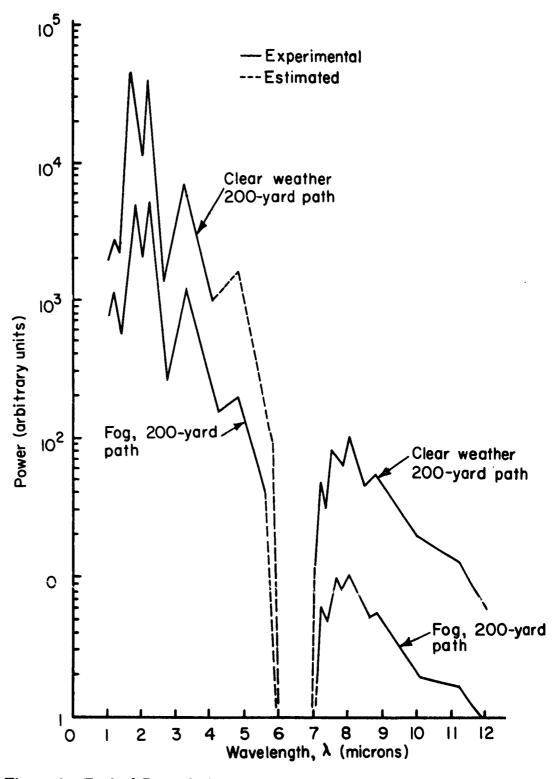


Figure 1. Typical Record of Normalized Spectrum of Carbon Arc Observed through a 200-yard Path in Clear Weather and Fog.

4. DISCUSSION OF RESULTS

The results of the particle size measurements are shown in Table 1 for fog data taken on 16 October 1959. (The particle counter was delivered on 12 October, but it was not until 16 October that the instrument was operating satisfactorily; hence, this is the only day for which reliable data are available. Transmission data and other parameters such as wind direction are given for all days in Tables 2 and 3. The measurements of visibility were taken at the National Bureau of Standard's visibility range about 500 yards from the infrared transmission path.)

The values for particle size are given in terms of the number of particles per cubic centimeter for size intervals of 0.5 to 1.0, 1.0 to 2.0, 2.0 to 4.0, 4.0 to 8.0, and 8.0 to 16.0 microns in radius. The columns are labeled with the mean radius of each interval; i.e., 0.75, 1.5, 3, 6, and 12 microns.

Junge's law, Eq. (1), was checked by plotting $n(r) \Delta r$, the number of particles per unit volume in radius interval Δr , against the mean particle radius in the interval on a logarithmic scale (see Figure 2). The negative slope of this curve is the value of p. Since a straight line can be drawn through the points in Figure 2, Junge's law applies to this fog.

An attempt was made to correlate the transmission observed through fog with Eq. (2) using the values of p, c, and r obtained from the analysis of the aerosol data. This equation, in principle, gives the absolute transmission as a function of wavelength. However, it is not directly useful for several reasons:

- (1) The transmission T is dependent on c. (Note that ln(1/T) = σL, where L is the path length.) Since sampling was made at a fixed point near the path, considerable variation in concentration may exist. Hence, correlation between the overall transmission and concentration is doubtful.
- (2) The use of a carbon arc which required readjustment at intervals may easily have disturbed the alignment of the system. Therefore, the absolute value of the measured transmission may not be accurate. The relative values for various wavelengths during a single run are not affected; thus, the shapes of the curves on a log plot of transmission are accurate.

An alternative approach was used to make the correlation. Equation (3), derived by differentiation from Eq. (2), is independent of the value of c. It is related to the shape of the experimental curve of log log reciprocal transmission vs. log λ by Eq. (4).

$$\frac{d(\ln \sigma)}{d(\ln \lambda)} = (3 - p) - \frac{r_1^{(3-p)} K(\frac{r_1}{\lambda})}{\int_0^{r_1/\lambda} (\frac{r}{\lambda})^{(2-p)} K(\frac{r}{\lambda}) d(\frac{r}{\lambda})} .$$
 (3)

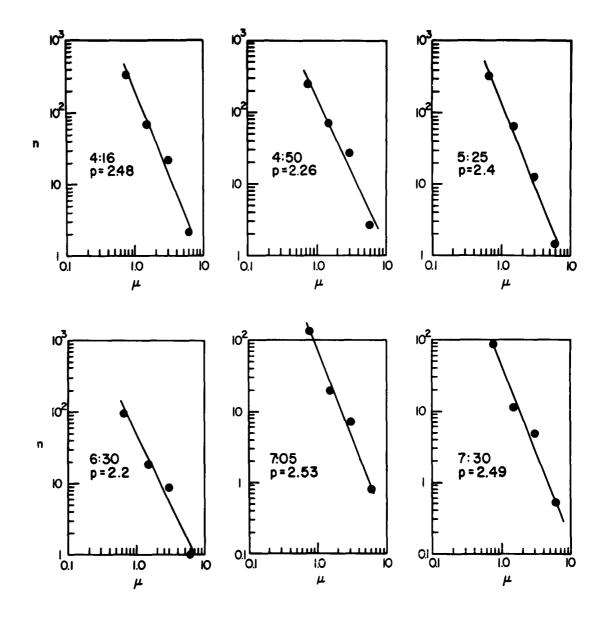


Figure 2. Selected Plots of n(r) vs r for Fog on the Morning of 16 October 1959.

$$\frac{d(\ln \sigma)}{d(\ln \lambda)} = \frac{d\left(\ln \ln \frac{1}{T}\right)}{d(\ln \lambda)} = \frac{d\left(\log \log \frac{1}{T}\right)}{d(\log \lambda)} \tag{4}$$

The values of p and r_4 should be the same throughout the fog. The second term on the right in Eq. (3) is of interest. For p>3 and a particular r_4 , this term is dependent on p and only slightly dependent on λ (or r_4/λ). For decreasing values of p<3, this term develops a "ripple" becoming increasingly dependent on r_4/λ . Since r_4 is at best an approximate value, a smoothed value should be used for $[d(\ln \sigma)]/[d(\ln \lambda)]$. The resulting smoothed value becomes positive for $2.2 (in the region <math>(r_4/\lambda) >> 1$). In this range of r_4/λ , the slope of the transmission data is zero or slightly positive (note dotted lines in Figure 3). For $(r_4/\lambda) < 1$ (Rayleigh scattering), $[d(\ln \sigma)/[d(\ln \lambda)]$ is always strongly negative and one should expect a rapid increase in transmission (decrease in $\ln \ln 1/T$). Such a change to increasing transmission occurs in the experimental data at about 10 microns, again, see Figure 3. The most to be said about r_4 from the experimental particle data is that it lies between 8 and 16 microns.

Therefore, within the limits of accuracy of the equipment, the experimental data tends to corroborate both Junge's law for particle size distribution and the theory for attenuation using this law.

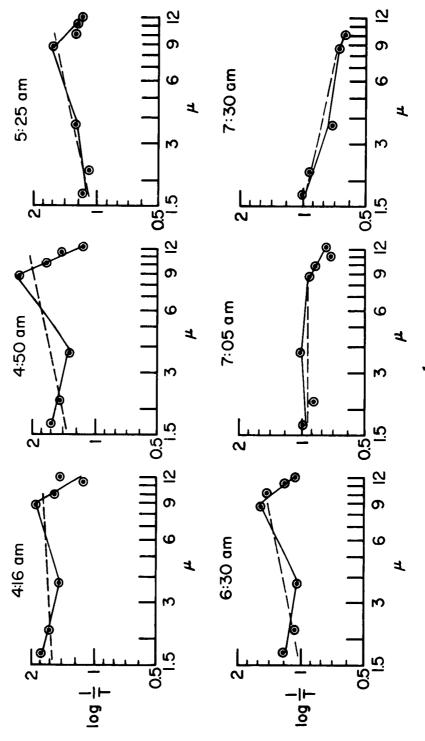


Table 1. Particle Size and Transmission Measured in Fog on 16 October 1959 at Arcata, California

| Time | Numbe | Number of Particles per cm ³ per Unit Radius Interval n(r)* | cles per nterval | $\frac{\text{cm}^3}{\text{n}(r)^*}$ pe | r Unit | ۵ | | | | $\operatorname{Log}\left(\frac{1}{T}\right)$ | | | |
|----------------------|----------|---|---------------------|--|-------------|-------|--------------------|---------------------|--------|--|---------|---------------------|-------------------|
| | r= 0.75µ | r= 1.5µ | r= 3µ | r= 6µ | $r = 12\mu$ | , | $\lambda = 1.7\mu$ | $\lambda = 2.2 \mu$ | λ=3.7μ | λ = 8 · 8μ | λ = 10μ | $\lambda = 11.2\mu$ | $\lambda = 12\mu$ |
| 4:00 A.M. | 275 | 71.5 | 21.2 | 1.59 | 0.000022 | 2.48 | 1.58 | 1.47 | 1.43 | 1.74 | 1.64 | 1.21 | 1.17 |
| 4:10 A.M. | ! | : | ; | ; | : | ! | 1.70 | 1.62 | 1.28 | 1.70 | 1.60 | 1.33 | 1.28 |
| 4:16 A.M. | 332 | 67.7 | 21.2 | 2.12 | 0.0088 | 2.48 | 1.77 | 1.60 | 1.49 | 1.89 | 1.52 | 1.20 | 1.46 |
| 4:35 A.M. | 332 | 60.5 | 31.8 | 2.68 | 0.0048 | 2.44 | ļ | ; | 1.08 | 2.05 | 1.52 | 1.33 | 1.28 |
| 4:45 A.M. | 314 | 57 | 23 | 5.6 | 0.003 | 2.45 | 1.66 | 1.50 | 1.50 | 2.04 | 1.85 | 1.35 | 1.48 |
| 4:50 A.M. | 237 | 2.99 | 25.9 | 5.6 | 0.0013 | 2.26 | 1.60 | 1.46 | 1.29 | 2.30 | 1.52 | 1.41 | 1.15 |
| 5:00 A.M. | 373 | 9.69 | 25.3 | 1.49 | 0.003 | 2.39 | 1.72 | 1.64 | 1.59 | 1.96 | 1.60 | 1.51 | 1.28 |
| 5:10 A.M. | 184 | 53.0 | 21.6 | 2.11 | 0.0008 | 2.15 | 1.73 | 1.55 | 1.56 | 2.05 | 1.70 | 1.51 | 1.28 |
| 5:15 A.M. | 250 | 50.0 | 12.5 | 1.56 | 0.003 | 29.2 | 1.52 | : | 1.28 | 2.05 | 1.47 | 1.33 | 1.16 |
| 5:25 A.M. | 319 | 64.4 | 12.8 | 1.42 | 8000:0 | 2.4 | 1.17 | 1.10 | 1.26 | 1.58 | 1.24 | 1.21 | 1.17 |
| 5:30 A.M. | 287 | 62.2 | 13.2 | 1.8 | 0.0035 | 2.4 | 1.34 | 1.11 | 1.18 | 1.70 | 1.31 | 1.20 | 1.28 |
| 5:40 A.M. | 213 | 38.3 | 7.91 | 1.12 | 0.0004 | 2.64 | 1.24 | 1.09 | 1.00 | 1.44 | 1.32 | 1.12 | 0.996 |
| 5:50 A.M. | 592 | 59.4 | 14.9 | 1.66 | 0.0015 | 2.44 | 1.47 | 1.42 | 1.30 | 1.66 | 1.32 | 1.12 | ! |
| 6:00 A.M. | 254 | 52.4 | 8.56 | 1.01 | 9000.0 | 5.69 | 1.15 | 1.04 | 1.14 | 1.51 | 1.41 | 1.26 | 1.06 |
| 6:10 A.M. | 236 | 48.7 | 8.11 | 0.89 | 0.0009 | 3.00 | 1.48 | 1.40 | 1.41 | 1.57 | 1.55 | 1.17 | : |
| 6:20 A.M. | 139 | 36.3 | 15.2 | 2.10 | 6000.0 | 2.07 | 1.02 | 0.958 | 1.00 | 1.16 | 1.15 | 0.946 | 0.924 |
| 6:30 A.M. | 95.1 | 18.5 | 8.81 | 1.02 | 0.00044 | 2.20 | 1.22 | 1.09 | 1.08 | 1.57 | 1.48 | 1.22 | 1.07 |
| 6:40 A.M. | 178 | 36.9 | 8.52 | 0.923 | 0.00263 | 2.56 | 0.793 | 992.0 | 0.743 | 1.06 | 1.03 | 0.872 | 0.801 |
| 6:45 A.M. | 168 | 32.3 | 9.12 | 1.12 | 0.0026 | 2.42 | 9.876 | 0.787 | 0.681 | 1.07 | 0.924 | 0.688 | 0.757 |
| 7:05 A.M. | 130 | 19.3 | 7.12 | 0.788 | 0.0013 | 2.53 | 0.987 | 0.893 | 1.01 | 906.0 | 0.860 | 0.721 | 0.757 |
| 7:20 A.M. | 100 | 11.2 | 4.48 | 0.588 | 0.0013 | 1.99 | : | : | 0.743 | - | : | ; | ! |
| 7:30 A.M. | 84.9 | 11.1 | 4.90 | 0.506 | 0.0004 | 2.49 | 1.01 | 0.916 | 0.711 | 0.657 | 0.625 | 0.167 | ! ! |
| 7:45 A.M. | 34.5 | 4.24 | 3.48 | 0.499 | 0.000.0 | 27.22 | 0.951 | 0.854 | 0.857 | 0.991 | 1.022 | 0.886 | 0.866 |
| "Clear" 2:15 P.M. | 23 | 3.45 | 0.78 | 0.056 | 0.000 | ! | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 00.00 |
| | | | | 1 | | | | | | | | | 1 |

*Note that n(r) is an average value derived by measuring the concentration of particles in radius interval Δr and dividing by the radius interval.

LAS-TN-E173-10

Experimental Transmission and Particle Count in Fog on 16 October 1959. Table 2.

| Velocity Direction (degrees) 3 | | | Per ce | ent of | Trans | Per cent of Transmission, | o u | | Particles. | Per | centa | te of F | Percentage of Particles | | Visible | Wind | Wind | Temperature |
|--|------------|-------|--------|--------|----------|---------------------------|------|------|------------|------|--------|---------|-------------------------|---------|-----------|----------|-----------|-------------|
| 3.4 3.7 8.8 1.0 11.2 1.2 1.4 8.8 1.6 1.6 1.0 <th>Time</th> <th></th> <th>Wave</th> <th>lengt</th> <th>I at at</th> <th>Micro</th> <th></th> <th></th> <th>per cm</th> <th>Å</th> <th>stweer</th> <th>Note</th> <th>d Size</th> <th></th> <th>Transmis-</th> <th>Velocity</th> <th>Direction</th> <th>(degrees</th> | Time | | Wave | lengt | I at at | Micro | | | per cm | Å | stweer | Note | d Size | | Transmis- | Velocity | Direction | (degrees |
| 2.4 5.3 1.6 6.8 265 54 27 16 2.4 0.0067 19 3 2.4 5.3 2.5 4.7 5.3 | | 1.7 | 2.2 | 3.7 | 8.8 | 9 | | 12 | | 1-2μ | 2-4µ | _ | 8-16μ | 16-32µ | cent) | | (degrees) | centigrade) |
| 3.4 3.7 1.8 2.3 6.1 6.8 2.0 2.4 6.4 0.0067 19 3 2.4 3.1 1.8 2.3 6.3 3.5 2.2 2.4 15 0.005 11 4 2.5 3.2 1.3 3.5 2.2 2.4 15 3.0 0.0128 11 4 3.2 3.4 4.7 5.3 3.03 55 2.0 21 3.0 0.0128 10 3.5 3.2 3.4 0.5 3.0 4.7 5.3 3.0 5.3 3.0 4.7 5.0 2.2 3.4 4.7 7.0 2.4 4.5 3.0 0.0043 1.2 2.2 2.2 3.0 0.0043 1.2 2.2 2.2 4.7 7.0 2.4 4.7 2.7 2.4 4.7 2.0 0.0043 1.2 2.2 2.2 4.7 2.0 0.0043 1.2 2.2 2.2 4.7 </td <td></td> <td></td> <td>,</td> <td></td> <td></td> <td>,</td> <td></td> <td></td> <td></td> <td></td> <td>,</td> <td>,</td> <td></td> <td>-,</td> <td>;</td> <td>•</td> <td></td> <td></td> | | | , | | | , | | | | | , | , | | -, | ; | • | | |
| 2, 4 5, 3 2, 0 2, 5 4, 7 5, 3 | 4:00 A. M. | | *: | | 0 | د. ع | | | 697 | 4 | 3 | 10 | 4 .7 | 0.0067 | 13 | n | 190 | 11 |
| 2.5 3.6 3.9 6.3 3.5 2.82 59 24 45 3.0 0.0025 11 4 8.0 0.9 3.0 4.7 5.3 3.03 55 20 21 3.6 0.0128 10 3.5 3.2 3.1 0.89 4.4 4.5 3.3 270 58 27 12 3.6 0.0043 22 2 2 0.0049 3.2 2 2 4.7 2.0 0.0048 4.7 2 2 0.0048 2 2 2 0.0048 3.2 2 2 2 0.0048 3.7 2 2 2 2 2 0.0048 3.7 2 2 2 2 2 2 3.0 0.0188 3 2 2 2 3.0 0.0048 3 2 2 2 4.3 0.0048 3 2 2 2 4.3 0.0048 3 | 4:10 A. M. | | 2.4 | 5.3 | 2.0 | 2.5 | 4.7 | | : | ; | : | ; | ; | : | ; | ! | : | 11 |
| 8.0 0.0 3.0 4.7 5.3 303 55 20 21 3.6 0.0128 10 3.5 3.2 3.1 0.0 3.4 4.5 3.3 270 58 21 17 3.8 0.009 12 2 3.5 5.1 0.5 3.0 3.9 7.0 247 48 27 2.2 0.0043 22 2 2.2 2.6 1.1 2.5 3.1 5.3 3.46 60 24 3.0 0.0188 22 2.2 4.3 0.0043 2.5 2 2.2 4.3 0.0048 2 2 2.5 4.3 0.0048 2 2.5 4.3 0.0048 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2 2 2 2 <td>4:16 A. M.</td> <td></td> <td>2.5</td> <td>3.2</td> <td>1.3</td> <td>3.0</td> <td></td> <td></td> <td>282</td> <td>59</td> <td>77</td> <td>15</td> <td>3.0</td> <td>0,0025</td> <td>11</td> <td>4</td> <td>150</td> <td>11</td> | 4:16 A. M. | | 2.5 | 3.2 | 1.3 | 3.0 | | | 282 | 59 | 77 | 15 | 3.0 | 0,0025 | 11 | 4 | 150 | 11 |
| 3.2 3.4 0.8 1.4 4.5 3.3 270 58 21 4.7 3.8 0.0043 12 2 3.5 5.1 3.0 3.0 3.0 2.47 48 27 21 4.2 0.0043 22 2 2.3 2.6 1.1 2.5 3.1 5.3 316 59 22 6.0 0.0048 27 2.5 2.8 2.0 0.9 3.4 4.7 7.0 208 60 24 12 0.0048 27 2.5 4.0 5.3 2.0 2.2 4.7 7.0 208 60 24 12 3.0 0.0048 27 2.5 3.0 | 4:35 A. M. | ; | ; | 8.0 | 6.0 | 3.0 | 4.7 | | 303 | 55 | 22 | 21 | 3.6 | 0.0128 | 10 | 3,5 | 115 | 11 |
| 3.5 5.1 0.5 3.0 3.0 7.0 247 48 27 21 4.2 0.0443 22 2 2.3 2.6 1.1 2.5 3.1 5.3 316 59 22 1.6 2.2 0.0078 14 2.5 2.8 2.8 2.9 3.1 5.3 196 47 27 22 4.3 0.0018 27 2.5 2.9 3.4 4.7 7.0 2.08 60 24 12 4.3 0.0018 27 2.5 3.0 5.5 2.6 5.7 6.1 6.2 2.2 4.0 0.0018 27 2.5 4.0 5.5 2.6 5.7 6.4 5.3 2.0 2.7 2.0 0.00149 2.7 2.5 8.1 5.0 5.2 5.2 5.2 5.2 5.0 0.00248 2.7 2.5 2.2 8.2 5.2 5.2 | 4:45 A. M. | | 3.2 | 3.1 | 0.89 | 1.4 | 4.5 | | 270 | 58 | 2.1 | 17 | 3.8 | 0.009 | 12 | 7 | 135 | 11 |
| 2.8 2.6 1.1 2.5 3.1 5.3 316 59 22 4.0 0.0048 14 2.5 2.8 2.9 2.0 3.1 5.3 196 47 27 22 4.3 0.0018 27 2.5 5.3 0.9 3.4 4.7 7.0 208 60 24 12 3.0 0.0148 31 2.5 8.0 5.5 2.6 6.3 5.3 259 60 26 13 0.01479 32 2.5 8.0 5.5 2.6 6.0 24 12 3.0 0.0148 3.1 2.5 8.1 5.6 1.0.1 1.66 64 23 9.5 2.7 0.0024 2.5 2.5 9.2 1.0.2 4.8 7.6 1.0.1 1.66 64 23 9.5 2.7 0.0024 2.5 2.5 9.2 1.2 2.0 2.2 | 4:50 A. M. | | 3.5 | 5.1 | | 3.0 | | 7.0 | 247 | 48 | 22 | 24 | 4.2 | 0.0043 | 22 | 7 | 100 | 11 |
| 2.8 2.9 2.0 3.4 5.3 496 47 27 22 4.3 0.0018 27 2.5 5.3 0.9 3.4 4.7 7.0 208 60 24 4.2 3.0 0.0148 31 2.5 8.0 5.2 6.3 6.3 6.3 5.3 2.5 60 26 10.0 0.01479 33 2.5 30 0.01479 32 2.5 30 2.5 30 0.01479 32 2.5 30 2.0 0.01479 32 2.5 30 2.5 30 0.01479 32 2.5 30 2.5 30 0.01479 32 2.5 30 0.01479 32 2.5 30 0.01479 32 2.5 30 0.01479 32 2.5 30 0.01479 32 2.5 30 0.01479 32 2.5 30 0.01479 32 2.5 30 0.01479 30 | 5:00 A. M. | | 2.3 | 2.6 | 1.1 | 2.5 | | | 316 | 59 | 22 | 16 | 2.2 | 0,0078 | 14 | 2.5 | 115 | 11 |
| 5.3 0.9 3.4 4.7 7.0 208 60 24 4.2 3.0 0.0418 31 2.5 8.0 5.2 2.6 2.6 2.6 2.6 4.0 0.00268 30 2.5 7.7 6.6 2.0 4.9 6.3 5.3 239 60 26 4.1 3.0 0.04179 32 2.5 8.2 10.0 3.6 4.8 7.6 10.1 166 64 23 2.7 0.00241 2.2 2.5 8.2 10.0 3.6 4.8 7.6 10.1 166 64 23 2.7 0.00241 2.7 2.5 9.2 1.2 4.8 2.01 63 2.6 4.9 4.0 6.0 2.6 4.0 0.0025 3.0 2.5 2.5 3.0 2.5 3.0 2.5 3.0 2.5 3.0 3.0 3.0 3.0 3.0 3.0 3. | 5:10 A. M. | | 2.8 | 2.8 | 6.0 | 2.0 | 3.1 | 5.3 | 196 | 47 | 27 | 77 | 4.3 | 0.0018 | 27 | 2.5 | 09 | 11 |
| 8.0 5.5 2.6 5.7 6.1 6.8 267 62 25 10 2.6 0.00268 30 2.5 7.7 6.6 2.6 4.9 6.3 5.3 239 60 26 11 3.0 0.01479 32 2.5 8.2 10.0 3.6 4.8 7.6 10.1 166 64 23 9.5 2.7 0.00211 21 2.5 2.5 3.9 2.7 0.00211 21 2.5 3.5 3.6 2.8 2.6 12 3.0 0.0025 3.6 2.5 3.0 0.0025 3.0 2.5 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 3.0 2.5 3.0 0.0025 < | 5:15 A. M. | | 1 | 5.3 | 6.0 | 3.4 | 4.7 | 7.0 | 208 | 09 | 77 | 12 | 3.0 | 0.0118 | 31 | | 325 | 11 |
| 7.7 6.6 2.0 4.9 6.3 5.3 239 60 26 41 3.0 0.01479 32 2.5 8.2 10.0 3.6 4.8 7.6 10.1 166 64 23 9.5 2.7 0.0021 21 2.5 3.8 5.0 2.2 4.8 7.5 228 58 26 12 3.0 0.0025 36 2.5 9.2 7.3 3.1 3.9 5.5 8.8 201 63 26 1.9 0.0025 36 2.5 4.0 3.9 5.5 8.8 201 48 26 20 0.0025 30 2.5 4.0 3.0 3.0 3.2 2.0 4.8 4.8 2.6 2.7 0.0048 2.5 2.5 4.0 4.0 4.1 4.8 4.8 2.4 4.8 4.8 2.6 4.0 0.0048 2.5 2.5 < | 5:25 A. M. | | 8.0 | 5,5 | 2.6 | 5,7 | | 6.8 | 267 | 29 | 25 | 10 | 2.6 | 0.00268 | 30 | 2,5 | 270 | 11 |
| 8.2 10.0 3.6 4.8 7.6 10.1 166 64 23 9.5 2.7 0.0021 21 2.5 3.8 5.0 2.2 4.8 7.5 228 58 26 12 3.0 0.0052 36 2.5 4.0 3.0 2.2 4.8 201 63 26 1.9 0.0025 30 2.5 4.0 3.9 5.5 8.8 201 4.9 0.0048 20 2.5 4.0 3.0 6.9 7.1 11.3 11.9 145 48 25 2.1 5.8 0.0048 20 2.5 4.0 1.0 6.0 7.1 11.3 11.9 145 48 25 2.1 2.0 0.0048 20 2.5 2.5 2.0 2.5 2.5 2.5 2.2 2.5 2.0 0.0044 20 2.5 2.5 2.6 0.0044 40 3.0 <td>5:30 A. M.</td> <td></td> <td>7.7</td> <td>9.9</td> <td>2.0</td> <td>4.9</td> <td></td> <td>5,3</td> <td>239</td> <td>09</td> <td>56</td> <td>11</td> <td>3.0</td> <td>0.01179</td> <td>32</td> <td>2.5</td> <td>Shifting</td> <td>11</td> | 5:30 A. M. | | 7.7 | 9.9 | 2.0 | 4.9 | | 5,3 | 239 | 09 | 56 | 11 | 3.0 | 0.01179 | 32 | 2.5 | Shifting | 11 |
| 3.8 5.0 2.2 4.8 7.5 228 56 12 3.0 0.0052 36 2.5 9.2 7.3 3.1 3.9 5.5 8.8 201 63 26 8.5 2.0 0.0025 30 2.5 4.0 3.9 2.7 3.8 6.8 188 63 26 9.0 1.9 0.0048 25 2 4.0 1.0 6.9 7.1 11.3 11.9 145 48 25 21 5.8 0.0048 20 2.5 2 4.0 1.0 1.0 1.0 0.0048 20 0.0048 20 2.5 2 | 5:40 A. M. | | | 10.0 | 3.6 | 4.8 | 9 | 10.1 | 166 | 49 | 23 | 9.5 | 2.7 | 0.00211 | 21 | 2,5 | Variable | 11 |
| 9.2 7.3 3.1 3.9 5.5 8.8 201 63 26 8.5 2.0 0.0025 30 2.5 2 4.0 3.9 2.7 2.8 6.8 188 6.3 26 9.0 1.9 0.0018 25 2 4.0 3.9 2.7 2.8 6.8 188 54 20 0.0048 20 2.5 2 3 3 3 3 3 3 | 5:50 A. M. | | | 5.0 | 2.2 | 4.8 | | ; | 228 | 58 | 97 | 12 | 3.0 | 0.0052 | 36 | 2.5 | Variable | 11 |
| 4.0 3.9 2.7 2.8 6.8 188 63 26 9.0 1.9 0.0018 25 2 41.0 10.0 6.9 7.1 11.3 11.9 145 48 25 21 5.8 0.0048 20 2.5 1 8.2 8.3 2.7 3.3 6.1 8.5 88 54 21 20 0.004 40 3.0 2.5 1 1 3.0 3.0 3.0 40 3.0 3.0 40 3.0 3.0 40 3.0 40 3.0 40 3.0 40 3.0 40 3.0 40 3.0 40 3.0 40 3.0 40 3.0 40 40 41.5 | 6:00 A. M. | | 9.5 | 7.3 | 3.1 | 3.9 | | 8.8 | 201 | 63 | 97 | 8.5 | 2.0 | 0.0025 | 30 | 2.5 | 45 | 11 |
| 41.0 10.0 6.9 7.1 11.3 11.9 145 48 25 21 5.8 0.004 20 2.5 8.2 8.3 2.7 3.3 6.1 8.5 88 54 21 20 5.8 0.004 40 3.0 17.0 18.0 8.8 9.4 13.4 15.8 142 63 23 12 2.6 0.0074 42 1.5 3.0 16.3 21.0 8.8 14.2 14.2 60 23 13 2.6 0.0074 42 1.5 1.5 16.3 21.0 8.0 14.2 14.0 60 23 13 2.0 1.5 | 6:10 A. M. | | 4:0 | 3.9 | 2.7 | 2.8 | 6.8 | ; | 188 | 63 | 92 | 9.0 | 4.9 | 0.0018 | 25 | 7 | 02 | 11 |
| 8.2 8.3 2.7 3.3 6.1 8.5 88 54 21 20 5.8 0.004 40 3.0 17.0 18.0 8.8 9.4 13.4 15.8 142 63 23 12 2.6 0.0074 42 1.5 2 1.5 | 6:20 A. M. | | 11.0 | 0.01 | 6.9 | 7.1 | 11.3 | 11.9 | 145 | 48 | 25 | 21 | 5.8 | 0.0048 | 20 | 2.5 | 105 | 11 |
| 17.0 18.0 8.8 9.4 13.4 15.8 142 63 23 12 2.6 0.0074 42 1.5 16.3 21.0 8.5 11.8 20.5 17.5 140 60 23 13 3.2 0.015 46 1.5 12. 14.6 17.7 21.3 29.8 | 6:30 A. M. | | | 8.3 | 2.7 | 3,3 | 6.1 | 8.5 | 88 | 54 | 21 | 20 | 5.8 | 0.00€ | 40 | 3.0 | 06 | 11 |
| 16.3 21.0 8.5 11.8 20.5 17.5 140 60 23 13 3.2 0.015 46 1.5 | 6:40 A. M. | 16.0 | 17.0 | 18.0 | 8.8 | 9.4 | | 15.8 | 142 | 63 | 23 | 12 | 5.6 | 0.0074 | 45 | 1.5 | 250 | 11 |
| 12.8 9.8 12.4 13.9 12.1 13.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 10.0 17.5 | 6:45 A. M. | | 16.3 | 11.0 | 80 10 | | | 17.5 | 140 | 09 | 23 | 13 | 3.2 | 0.015 | 46 | 1,5 | 190 | 11 |
| 42.8 9.8 12.4 13.8 19.0 17.5 10.0 44 3.1 0.010 44 3.0 18.0 73 69 15.4 6.9 3.2 0.0143 60 3.5 42.1 19.5 22.6 23.7 68.0 65 47 15 3.1 0.0054 74 3.9 44.0 13.5 22.6 23.7 44 23 6.6 0.0054 74 3.9 44.0 13.9 13.0 13.6 3.2 57 14 23 6.6 0.000 25 2 45.0 10.0 | 6:55 A. M. | | : | | 14.6 | ۲. | | 29.8 | ; | ; | ; | : | 1 | | 1 | : | 1 | 11 |
| 18.0 73 69 15.4 6.9 3.2 0.0143 60 3.5 12.1 19.5 22.6 23.7 68.0 65 17 15 3.1 0.0054 74 3.9 14.0 13.5 13.6 32 57 14 23 6.6 0.000 25 2 1.0 0.7 0.95 1.5 2.0 2.4 3.9 10< | 7:05 A. M. | | | | 12.4 | 80 | | 17.5 | 102 | 2 | 19 | 77 | 3.1 | 0.010 | ‡ | 3.0 | 135 | 11 |
| 12. 1 19.5 22. 6 23. 7 68.0 65 65 17 15 3.1 0.0054 74 3.9 14.0 13.9 10.2 9.5 13.0 13.6 32 57 14 23 6.6 0.000 25 2 1.0 0.7 0.95 1.5 2.0 25 2 100 100 100 100 100 160 <t< td=""><td>7:20 A. M.</td><td></td><td>1</td><td>18.0</td><td>;</td><td>-</td><td>;</td><td>i</td><td>73</td><td></td><td>15.4</td><td>6.9</td><td>3.2</td><td>0.0143</td><td>09</td><td>3,5</td><td>150</td><td>11</td></t<> | 7:20 A. M. | | 1 | 18.0 | ; | - | ; | i | 73 | | 15.4 | 6.9 | 3.2 | 0.0143 | 09 | 3,5 | 150 | 11 |
| 14.0 0.7 0.95 1.5 13.6 <t< td=""><td>7:30 A. M.</td><td></td><td>12. 1</td><td>19.5</td><td>22.6</td><td></td><td>68.0</td><td>:</td><td>99</td><td>99</td><td>11</td><td>15</td><td>3.1</td><td>0.0054</td><td>2</td><td>3.9</td><td>98</td><td>11</td></t<> | 7:30 A. M. | | 12. 1 | 19.5 | 22.6 | | 68.0 | : | 99 | 99 | 11 | 15 | 3.1 | 0.0054 | 2 | 3.9 | 98 | 11 |
| 4.0 0.7 0.95 1.5 2.0 2.4 400 400 400 400 46 72.4 22 4.9 .25 0.000 95 5 | 7:45 A. M. | | 14.0 | 13.9 | 10.2 | .5 | | 13.6 | 32 | 57 | 1, | 23 | 9.9 | 000.0 | 25 | 7 | 160 | 11 |
| 400 100 100 100 100 100 100 16 72.4 22 4.9 .25 0.000 95 5 | 7:50 A. M. | 0, 68 | | | | | 1.5 | 2.0 | ; | 1 | | : | : | ł | ; | 2.4 | 135 | 11 |
| | 2:15 P.M. | 100 | 100 | | _ | 100 | 100 | 100 | 16 | 72.4 | 22 | 4.9 | . 25 | 000.0 | 9.5 | ĸ | 300 | 11 |

*Particles were counted for a period of 3 minutes beginning at each time listed. Total number of particles counted varied from 4000 to 90,000 in the 3-minute interval.

Table 3. Experimental Infrared Transmission through Fog.

| Wind * | Direction | | | | |
|--|-------------|------------|--------------|---|------------------------|
| Wind | Velocity | | | ბოოე 20 10 10 10 10 10 10 10 10 10 10 10 10 10 | 2.5 |
| Visible | ransmission | (Per cent) | | 22422444444222 | 96 |
| | | 12 | | no measurable transmission | 100 |
| no | | 11.2 | October 1959 | no measurable transmission | 100 |
| ansmissi n Micron | | 10 | 3 Octo | no measurable transmission | 100 |
| Per cent of Transmission Wavelengths in Microns | 9 | 8.8 | | no measurable transmission | 100 |
| Per c | | 2.2 | | 0.80 0.17 0.03 0.04 0.002 0.01 0.01 0.01 0.01 0.01 0.01 0.0 | 100 |
| | | 1.7 | | 0.70 0.26 0.19 0.03 0.01 0.01 0.01 0.01 0.02 0.00 0.00 0.00 | 100 |
| | Time | | | 4:35 P. M. 4:45 P. M. 4:50 P. M. 5:20 P. M. 7:15 P. M. 7:25 P. M. 7:25 P. M. 7:45 P. M. 7:45 P. M. 8:30 P. M. 8:30 P. M. 9:50 P. M. 9:50 P. M. 10:15 P. M. | 4 Oct. 59 3:30 P.M. |

*Wind direction can be obtained from the National Bureau of Standards installation at Arcata, California.

Table 3 (continued)

| Wind * | 7110011011 | | | | | *** | | | | | | | | | • | | | | | | | | | | | | | | |
|--|------------|-----------|--------------|-----------|-----------|-----|-----|--------------|-----------|----|-----|-----------|-----|-----|-----|------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|
| Wind | retocaty | | | 5*9 | z, | 4 | 3.5 | | 10 | 6 | 8.5 | 11.5 | 10 | œ | 6.5 | 5 | 4 | 13.5 | 4.5 | 3.5 | 3.5 | 2.5 | 6.5 | 7.5 | 6.5 | 7.5 | 10.0 | 2.5 | 1.5 |
| Visible Transmission | (Per cent) | (2000 - 1 | | 85 | 82 | 96 | 91 | | • | 52 | 56 | 72 | 40 | 35 | 36 | 10 | 9 | 9 | 1 | 30 | 52 | 20 | 10 | 80 | 70 | 80 | 80 | 96 | 94 |
| | ,, | 12 | | 150 | 09 | 70 | 100 | | 5.0 | 52 | 53 | 95 | 6.7 | 13 | 6.7 | 10.1 | 6.7 | 8.4 | 52 | 25 | 39 | 26 | 139 | 168 | 143 | 120 | 196 | 105 | 100 |
| on, s | , | 11.2 | October 1959 | 140 | 71 | 77 | 100 | October 1959 | 7.3 | 88 | 7.1 | 139 | 23 | 21 | 7.2 | 12.5 | 9.4 | 11.5 | 25 | 09 | 89 | 82 | 162 | 193 | 143 | 126 | 205 | 130 | 100 |
| er cent of Transmission, Wavelengths in Microns | 9 | 10 | 8 Oct | 190 | 57 | 100 | 100 | 9 Oct | 6.4 | 57 | 29 | 39 | 21 | 38 | | 9.6 | 7.1 | 10.6 | 32 | 74 | 55 | 98 | 159 | 172 | 125 | 129 | 195 | 108 | 100 |
| nt of Tra engths in | | 8.8 | | 150 | 73 | 81 | 100 | | 10 | 1 | 100 | 106 | 17 | | ^1 | | | | | 5.9 | | | | | | | | | |
| Per cer Wavel | | 2.2 | | 160 | 140 | 100 | 100 | | | 93 | 93 | 170 | 44 | 123 | 2.7 | 9.5 | 2.4 | 2.1 | 2.3 | 52 | 88 | ; | 94 | 200 | 167 | 162 | 195 | 150 | 100 |
| | | 1.7 | | 150 | 120 | 93 | 100 | | | 85 | 92 | 170 | 41 | 108 | 2.6 | 9.7 | 2.0 | 1.8 | 2.0 | 23 | 92 | 1 | 74 | 180 | 155 | 152 | 169 | 134 | 100 |
| | Time | | | 9:10 A.M. | 9:25 A.M. | Ŕ | Ą. | | 7:30 A.M. | Ř | | 8:40 A.M. | Ŕ | Ä | | Ÿ | ď | Ŕ | Ķ | Ä | ġ. | Ä | Ą | Š | Ä | Ä | Ř | σ, | ď. |

Table 3 (continued)

| Wind | Direction* | | | | | | | | | | | | | 108 | 180 | 162 | 144 | 139 | 54 | 99 | 54 | 95 | 171 | 147 | 135 | 216 | 167 | 176 | 202 | 300 |
|---------------|-----------------------|------------|-------------|-----------|--------|------|--------|--------|--------|--------|-----|--------|-------------|-------|------|---------|---------|-------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------------------------|
| Wind | Velocity | , | | ; | ļ | ; | ; | t í | 1 | ; | 1 | 1 | | ĸ | • | 5.5 | • | • | • | • | • | • | • | • | • | • | 3.0 | • | • | 2 |
| Visible | Transmission | (Per cent) | | ហ | 8 | 4 | : | 34 | 40 | 06 | 65 | 96 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 95 |
| | | 12 | 6 | | | 4.7 | • | 46 | 49 | 121 | 87 | 100 | 6 | r | 10 | m | ea | LSI | ır | ab | le | tı | a | ns | m | is | si | on | | 100 |
| ion, | su | 11.2 | October 195 | | | 2.0 | • | 51 | 99 | 104 | 74 | 100 | October 195 | r | 10 | m | ea | LSI | ır | ab | le | tı | rai | ns | m | is | si | on | | 100 |
| Transmission, | avelengths in Microns | 10 | 12 Oc | | | 9.0 | | 37 | 39 | 46 | 120 | 100 | 14 Oc | r | 10 | m | ea | 1.51 | ır | ab | le | tı | ra | ns | m | is | si | on | | 100 |
| cent of Tr | elengths | 8.8 | | 1.7 | 2.8 | 0.92 | • | 23 | 35 | 64 | 29 | 100 | | n | 10 | m | ea | su | ıra | ab | le | tr | aı | 18: | m | is | sic | on | | 100 |
| Per c | Wav | 2.2 | | | | 1.8 | • | • | | | 26 | | | • | • | • | • | • | • | • | • | • | • | • | • | • | 0.010 | • | • | 100 |
| | | 1.7 | | | • | 1.7 | • | • | ö | 54 | 9 | 100 | | 0.007 | 0.12 | 0.019 | 0.013 | 0.016 | 0.106 | 0.052 | 0.213 | 0.065 | 0.008 | 0.009 | 0.008 | 0.032 | 0.007 | 0.011 | 0.010 | 100 |
| | Time |) | | 7:25 A.M. | :35 A. | Ķ | :55 A. | :02 | :15 A. | :25 A. | :30 | :40 A. | | | ď, | 2:05 A. | 2:30 A. | Ā | 2:55 A. | Ą. | Ķ | Ķ | ¥ | Ŕ | Ķ | Ą | Ŕ | | :25 A. | 16 Oct. 59 2:15 P. M. |

LIST OF REFERENCES

- Kurnick, S. W., Zitter, R. N., and Williams, D. B., <u>Atmospheric Transmission</u>
 in the Infrared During Severe Weather Conditions. The University of Chicago,
 Laboratories for Applied Sciences, Report No. CML-TN-P: 45-3, May 1959
 (Unclassified).
- 2. Kurnick, S. W., Zitter, R. N., and Williams, D. B., "Attenuation of Infrared Radiation by Fogs" JOSA, 50:6 (June 1960) 578-583.
- 3. Gumprecht-Sliepcevich, <u>Light Scattering Functions for Spherical Particles</u>, The University of Michigan, 1951.
- 4. Penndorf, R., "Mie Scattering Coefficient for Water Droplets in Air," Meteorol., 13: 2(1956) 219.

| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED |
|--|--|---|--------------|
| AD- AF Cambridge Research Center, Bedford, Mass. RESEARCH ON ATMOSPHERIC ATTENUTION OF INFRARED RADIA- TION, by Howard T. Betz. Dec 1960. 13 pp.incl. illus. (Proj. 4991; Task 49910) LAS-TN-E173-10 (AF 19(604)-5877) | This report summarizes the results of a measurement program conducted at Air Force Cambridge Research Genter Fog Site at Arcata, California. The purpose of the Arcata fog experiment was (1) to collect data permitting a test of the application of the condet of the collect data permitting a test of the applications. | bility of Junge's law of the distribution of particle size as a consistent phenomenon of fogs and (2) to verify the predicted values of transmission based upon particle size distribution. The experimental data presented tend to corroborate both Junge's law for particle size distribution and the theory for attenuation using this law. | |
| | bility of Junge's law of the distribution of particle size as a consistent phenomenon of fogs and (2) to verify the predicted values of transmission based upon particle size distribution. The experimental data presented tend to corroborate both Junge's law for particle size distribution and the theory for attenuation using this law. | AF Cambridge Research Center, Bedford, Mass. RESEARCH ON ATMOSPHERIC ATTENUATION OF INFRARED RADIATION, by Howard T. Betz. Dec 1960. 13 pp incl. illus. (Proj. 4991; Task 49910) LAS-TN-E173-10 (AF 19(604)-5877) Unclassified Report This report summarizes the results of a measurement program conducted at Air Force Cambridge Research Center Fog Site at Arcata, California. The purpose of the Arcata fog experiment was (1) to collect data permitting a test of the applica-(over) | AD- |
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED |

er i sea Mass c